Investigating Wave Processes Important to Air-Sea Fluxes Using Infrared Techniques

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LONG-TERM GOALS

The long-term goal is to understand the wave-related mechanisms that regulate and produce variability in air-sea fluxes under low to moderately-high wind conditions.

OBJECTIVES

The first objective is to use infrared techniques to determine both the wave-related surface processes and their respective rates of air-sea exchange. The second objective is to combine these data with turbulence and air-sea flux measurements by myself and other investigators to determine the extent to which variability in air-sea fluxes is related to wave phenomena.

APPROACH

One of the central objectives of air-sea interaction is to identify the mechanisms responsible for the fluxes of momentum, heat and humidity throughout the lower atmospheric boundary and oceanic surface layers. During the Waves, Air-Sea Fluxes, Aerosols, and Bubbles (WASFAB) Experiment in October/November of 2005, we have continued to investigate the statistics of a continuum in spatial and temporal scale of wave-related (e.g., microbreaking, whitecapping, Langmuir circulation) and upper-ocean (e.g., free-convection and shear) processes at the air-sea interface that are relevant to the fluxes of heat, mass and momentum throughout the lower atmospheric boundary and oceanic surface layers in low to moderately high winds. The approach is to make field measurements of wave-related processes that affect the ocean surface skin temperature using two complementary infrared (IR) techniques. An IR/Video imaging system provides high spatial and temporal resolution of the surface processes while the active controlled flux technique (ACFT) quantifies the surface transfer processes with comparable resolution. The high spatial coverage and fine spatial and temperature resolution of our systems allowed us to examine spatial scales in transfer processes that span the oceanic and marine boundary layers of *O*(10 m) down to fine-scale processes of *O*(1 cm). The intensive field experiment took place at the Field Research Facility of the Army Corp of Engineers in collaboration with G. de Leeuw (TNO), M. Smith (University of Leeds), W. McGillis (LDEO), and M. Banner (LDEO). I made measurements of the sea surface temperature using a CEDIP model Jade LWIR longwave (8-9.3 μm) IR imager (320 x 240 pixels) with a sensitivity of 0.02°C. Radiometric temperature of the sea and sky were measured with down- and up-looking Heitronics model KT-15 radiometers (8-14 μm). An Imperx digital video camera (1000 x 1000 pixels) synchronized with the Jade camera was implemented to characterize the sea surface condition and visible wave processes such as whitecapping.

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During WASFAB, we implemented proven laboratory techniques in the field using an 8-m boom extending out from the end of the 560-m pier in 7-m deep water well outside the surf zone. We identified wave-related processes with spatial scales of *O*(0.01m) to *O*(10m) and characterized their statistical properties. In particular, the Active Controlled Flux Technique was collocated with high-resolution wave measurements, direct covariance air-sea fluxes, and near-surface oceanic turbulence to investigate the modulation of SST and fluxes caused by the interaction between swell and wind waves that affects the intermittency in large-scale and micro-breaking. The infrastructure at FRF provides a wealth of mean atmospheric, ocean, and wave measurements and allows us to implement the operator-intensive IR techniques.

Specific objectives of the experiment at the FRF ACE in Duck NC are to:

A. determine the temporal and spatial scales of processes that cause turbulent disruptions of the aqueous thermal boundary layer (TBL).

B. quantify both the mean rates of exchange and the individual process-driven rates of exchange for the turbulent disruptions of the TBL identified above.

C. assess the relative roles and potential contribution that individual processes have on the heat flux.

D. compare the heat flux derived from ACFT, the direct flux estimates, and estimates of the heat flux from existing parameterizations.

WORK COMPLETED

A major effort was put forth in completing WASFAB, the intensive field experiment that was performed at the FRF in Duck, NC in October of 2005. Near-surface ocean turbulent dissipation rates and direct air-sea fluxes of heat and mass were measured along with IR and video imagery, including the active controlled flux technique, as well as high resolution wave measurements. Following the intensive field experiment at Duck in October 2005, the narrow field-of-view (FOV) radiometer and atmospheric direct flux systems remained installed at FRF to make long-term measurements and capitalize on existing atmospheric, oceanic, and surface wave measurements at FRF. I have set up a quick view website for observation and quality control of both the WASFAB data (http://www.ldeo.columbia.edu/~felixt/ocp/zappa/Duck_2005/index.html) and the long-term data (http://www.ldeo.columbia.edu/~felixt/ocp/zappa/Duck_Longterm/index.html). Examples of the IR and video movies can be found at (http://www.ldeo.columbia.edu/~felixt/duck).

The data have been analyzed, and the key results are described below and are in preparation for publication in the *Journal of Geophysical Research*. These results and other segments of these preliminary investigations were presented at the European Aerosol Conference in September 2005, and the1st Symposium of the Atmospheric Composition Change European Network of Excellence: The Changing Chemical Climate of the Atmosphere in September 2005, the AGU Ocean Sciences Meeting in February 2006, the General Assembly of the European Geosciences Union in April 2006, and the International Workshop on Transport at the Air Sea Interface in September 2006 [*De Leeuw et al., 2006a, b, c, d; Zappa et al. 2006a, b*]. I have also submitted a groundbreaking manuscript that is closely related to this project [*Zappa et al*. 2006c].

RESULTS

The results reported in the previous Annual Report for this Award from the coastal ocean at FRF in Duck, NC were compared to those from a macro-tidal river estuary with wind and tidal forcing, a large tidal freshwater river, and a model ocean. The results clearly show that transfer under wind, waves, currents, rain, and surfactants indeed scales with the hypothesized model based on the turbulent dissipation rate over a wide range of environmental systems with different types of environmental forcing and processes. The effects of bubbles needs to be considered for the case at high winds in the coastal ocean when the exchange is likely to be enhanced relative to the air-sea transfer model based on the turbulent dissipation rate. The results of the pilot projects demonstrated both the feasibility of the proposed techniques and the need to determine the wave-related effects on air-sea fluxes that was addressed during the intensive field experiment in October 2005 at FRF in Duck, NC and the ongoing long-term measurements at FRF.

Sea surface skin temperature (SST) is a controlling factor in the air-sea flux of latent and sensible heat, and it is modified by the presence of swell waves. Miller and Street [1977] observed SST modulation in the laboratory that shifts from downwind to upwind side with wind speed. Simpson and Paulson [1980] observed from R/P FLIP a peak in the coherence spectra between SST and wave height occurs at the peak wave frequency. The observed that the phase angle between the SST and wave height at the peak wave frequency is -30°, indicating warm SST on the upwind side of the crest and suggested it was due to locally enhanced wind stress that thins TBL. They also observed that the phase spectrum increases from -30° at 0.06 Hz to 100° at 0.4 Hz, implying that at 0.4 Hz warm SST fluctuations associated with steep gravity waves were downwind of the crest and suggested it was due to the generation of turbulence from surface instabilities or the enhancement of capillary waves. Jessup and Hesany [1996] also observed from R/P FLIP variability in the phase of the SST modulation as a function of relative wind swell direction. For the wind and swell aligned, the maximum SST modulation occurs on the downwind side of the swell. For the wind and swell opposed, the phase changes by roughly 180° corresponding to the rear face (again the downwind side). They suggest that microbreaking is a mechanism that is consistent with the shift in phase depending on the alignment of the wind and swell.

We only look at onshore winds and do not vary the alignment of the wind and swell. Figure 1 shows the phase angle of the coherence between SST and wave height as a function of wind speed (positive phase means the SST leads the surface wave). Here, the phase angle is an average within the wave frequency band of 0.2 to 0.6 Hz. Similar results are observed for the phase angle chosen at the peak significant wave frequency. We observe that at low wind speeds the phase is positive (on the downwind side of the wave) and as the wind speed increases, the phase angle shifts to the upwind side of the crest. This behavior is similar to the laboratory measurements of Miller and Street [1976] that the phase shifted from positive phase with increasing wind speed, and this wind speed dependence was not reported from the field data by either Simpson and Paulson [1980] or Jessup and Hesany [1996]. The shift in the phase angle change from the downwind side of the crest to the upwind side is also correlated with an increase in significant wave height. Is this shift related to wave processes? And do we observe an enhanced flux that is related to the coherence between SST and wave height?

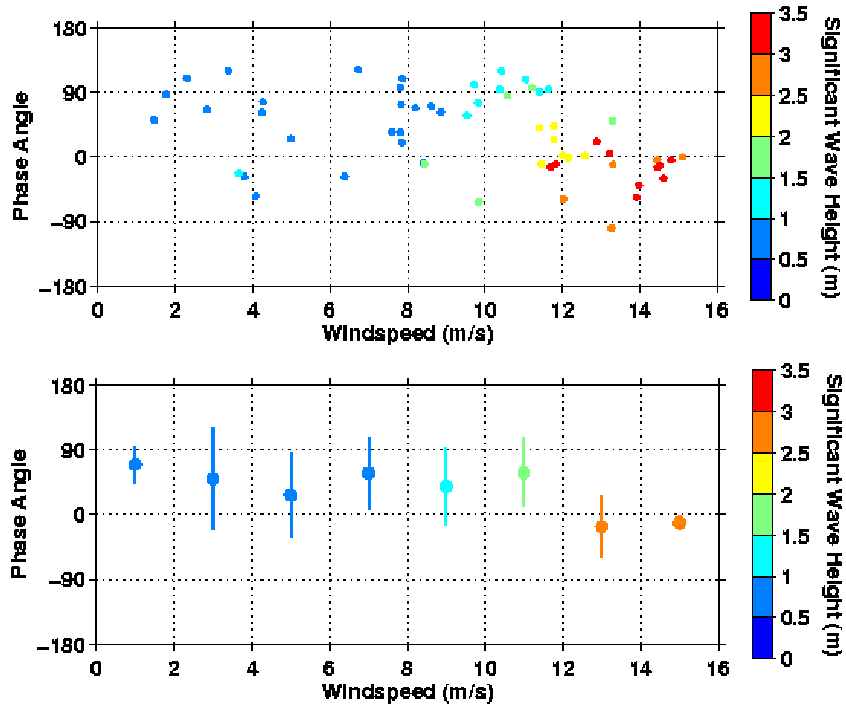

Figure 1. Top: Phase angle of the coherence between SST and wave height as a function of wind speed. Color bar represents significant wave height. Bottom: Same as Top only bin averaged in 1 m s-1 bins. Measured at the Field Research Facility in Duck, NC in 2004. Positive phase means the SST leads the surface wave.

Measurements quantified the exchange rates, and their modulation, associated with these small-scale processes important in promoting the air-sea fluxes as well as compare the directly measured heat flux and the heat flux inferred from IR techniques. Figure 2 shows the normalized heat flux, k* = Qcft/Qnet, as a function of the wave phase for varying wind and wave states, where Qcft is determined from the active controlled flux technique and Qnet is the net heat flux determined from the direct covariance sensible and latent heat fluxes, the net solar flux, and the longwave flux. The active controlled flux technique allows for the local determination of the heat flux and the evaluation of the existence of the modulation of the heat flux by waves and their associated small-scale processes. At low wind speeds and low significant wave height (3.2 m s-1 and 0.9 m), we see no phase relationship in k* which is similar to laboratory measurements of microbreaking where the highly wind-forced system has minimal swell influence. At moderate wind speeds and swell (7.5 m s-1 and 2.3 m), we begin to see the influence of the swell and the enhancement of the flux on the forward face of the swell in tandem with dominance in the existence of microbreaking. For the biggest waves and highest winds encountered during WASFAB (14.0 m s-1 and 3.5 m; individual waves reached 6 m at times), we clearly observe a shift in the enhanced flux to the rear face that is dominated by the presence of turbulent wakes of whitecapping breaking waves.

In summary, we have shown that the phase between SST and wave height shifted from positive to negative phase with increasing wind speed, this phase change also related to an increase in significant wave height, the heat flux due to waves is enhanced by 20% to 40%, k* also shows modulation along the phase of the wave that coincides with the shift in modulation of SST and is associated with a shift in process from microbreaking to whitecapping.

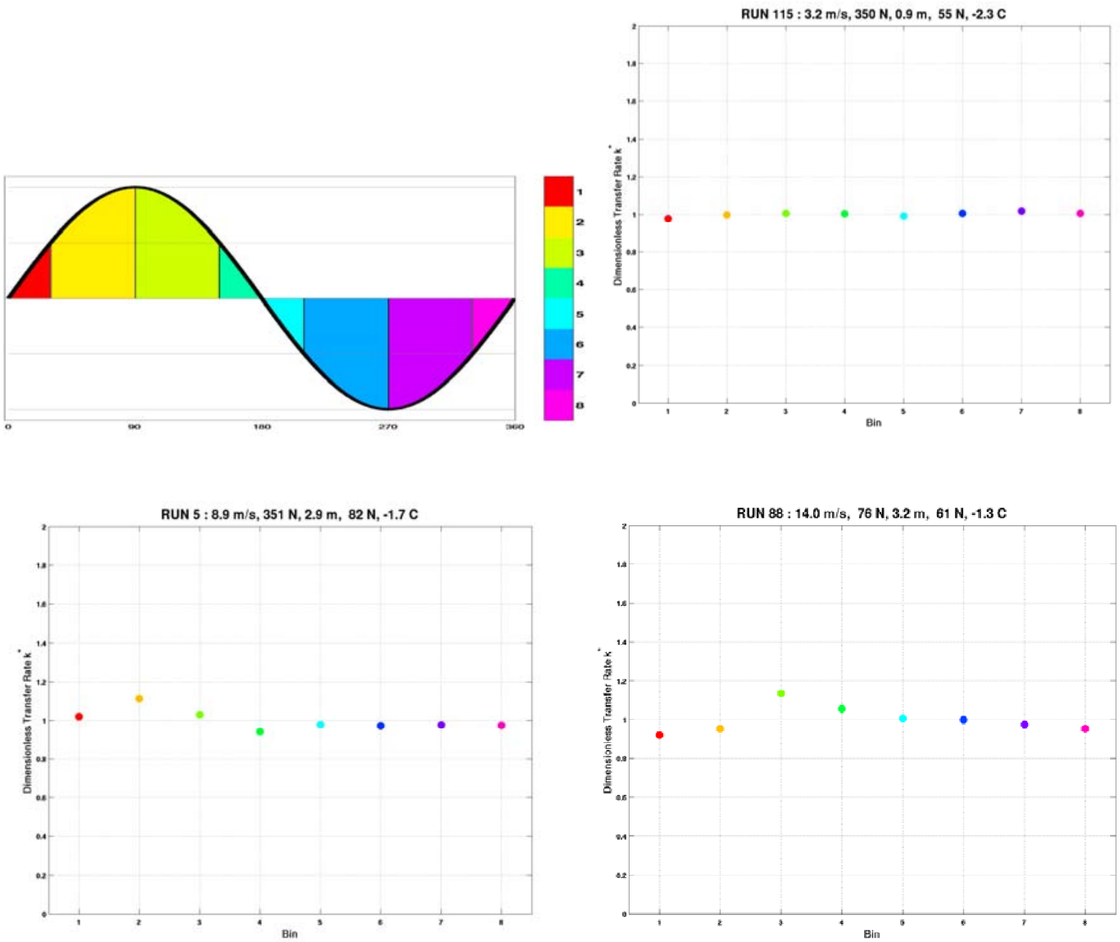

Figure 2. Normalized heat flux, k*, as a function of wave phase for varying wind and wave states. Top Left: Color table that describes the wave phase at which each subsequent measurement occurs. The crest of the wave occurs between the yellow and the light green bins while the trough is between the blue and the purple. Wave propagation is from right to left. Top Right: k* for wind speed of 3.2 m s-1 and significant wave height of 0.9 m. Bottom Left: k* for wind speed of 7.5 m s-1 and significant wave height of 2.3 m. Bottom Right: k* for wind speed of 14.0 m s-1 and significant wave height of 3.5 m. Note the shift from no modulation, to enhanced flux on the downwind face, to enhanced flux on the upwind face.

We continue to make micrometeorological and wave measurements at the US Army Corps of Engineers Field Research Facility (FRF) in Duck, NC (FRF pier). The aim of the long-term measurements is to build a database to study momentum, heat and mass air-sea fluxes and their effects on waves, in particular during high wind speeds. The Objective of the long term observations at FRF is to develop a data base that will be used to describe the physical relationships between wind history, wave field development, and atmospheric drag during high wind speed events, through the determination of wind speed and stability dependence of drag coefficients. The rationale for this work is that the WaveWatch III model over-predicts wave heights at high winds speeds. One potential reason is that the momentum flux to the waves is overestimated within the model. Recent results indicate that the momentum flux at wind speeds above 30-40 m s-1 plateaus [*Powell et al.*, 2003] and may lead to a reduction in the drag coefficient used in the WaveWatch III model. This reduced drag will lead to more representative wave conditions.

Wind speed dependencies of the drag coefficients determined from the LDEO sonic covariances at the end of the boom at 10 m height are shown in Figure 3, for all the on-shore data measured during the winter of 2006. Data obstructed by the pier that will cause flow distortion as discussed above have been excluded. Initial results from meteorological measurements during the WASFAB experiment in October 2005 through the August 2006 show that onshore wind conditions are representative for open ocean conditions when compared to the TOGA-COARE parameterization [*Zappa et al*. 2006b]. The bin-averaged data show incredible agreement with the TOGA-COARE algorithm between winds speeds of roughly 4 m s-1 to 18 m s-1. The divergence of the data from the TOGA-COARE algorithm at low winds speeds below 4 m s-1 is characteristic for the stable boundary conditions that were prevalent during these low wind conditions. The divergence of the data from the TOGA-COARE algorithm at high winds speeds above 18 m s-1 must be taken with caution due to the low data density. While the wind speeds in these experiments were only up to 18 m s-1, the planned long-term deployment at FRF is aimed for extreme wind speeds up to at least 40-50 m s-1 that may occur during storm conditions. The long-term objective is wave model prediction at high wind speed using improved parameterization of atmospheric inputs and understanding of the dependencies of the air-sea fluxed on wave age, mixed sea states (coupled systems of wind seas and swell from various directions), and low-level jets that may develop over the swell under low-wind conditions (breakdown of M-O similarity.

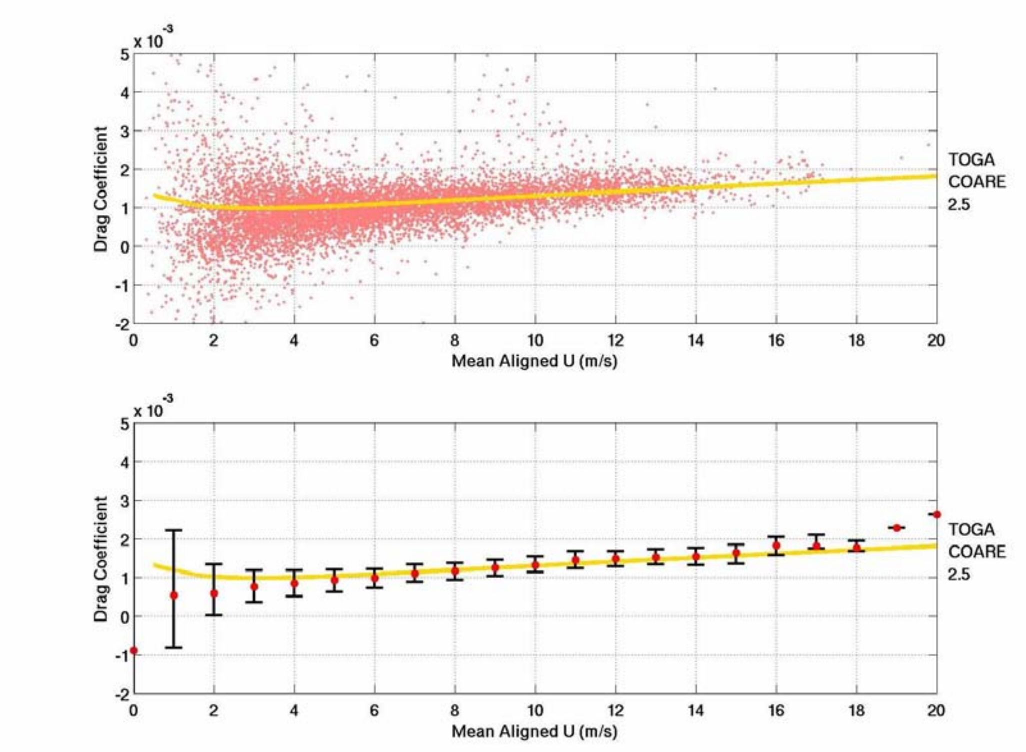

Figure 3: Drag coefficient, CD, as function of wind speed for on shore wind (WD=330-180o) for the complete winter 2006 data collection season. CD was determined using the measured LDEO sonic covariances for individual data realizations in pink (Top) and averaged into 1 m s-1 bins in red with variability bars. Also plotted is the TOGA-COARE 2.6 parameterization in yellow for drag coefficient over the open ocean.

IMPACT/APPLICATIONS

The encouraging results of our initial measurements at the FRF in Duck, NC in comparison with my results from other systems demonstrate that we are able to quantify the wealth of processes that control air-sea fluxes and scale the rate of transfer by the turbulent dissipation rate. The impact of our analysis and observations will be to improve parameterizations of air-sea heat flux.

RELATIONSHIP TO OTHER PROGRAMS OR PROJECTS

This project has evolved into a collaboration with G. de Leeuw of TNO and M. Smith of the University of Leeds. I have also continued to work closely with W. McGillis (LDEO) and M. Banner (LDEO) to correlate the IR signatures with directly measured fluxes and surface-roughness/wave-slope measurements.

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